SENSITIVITY OF SIMULATED WARM RAIN FORMATION TO COLLISION AND COALESCENCE EFFICIENCIES, BREAKUP, AND TURBULENCE: COMPARISON OF TWO BIN-RESOLVED NUMERICAL MODELS

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1. INTRODUCTION

Numerical models that resolve cloud particles into discrete mass size distributions on an Eulerian grid provide a uniquely powerful means of studying the closely coupled interaction of aerosols, cloud microphysics, and transport that determine cloud properties and evolution. However, such models require many experimentally derived paramaterizations in order to properly represent the complex interactions of droplets within turbulent flow. Many of these parameterizations remain poorly quantified, and the numerical methods of solving the equations for temporal evolution of the mass size distribution can also vary considerably in terms of efficiency and accuracy. In this work, we compare results from two size-resolved microphysics models (Ackerman et al. 1995; Seifert and Beheng 2001) that employ various widely-used parameterizations and numerical solution methods for several aspects of stochastic collection.

2. INITIALIZATION

We perform all of our tests using a box model initialized with a gamma distribution of droplets at the 1000 mb level. Fall velocities are taken from Rogers et al. (1993), where necessary, although evolution in the box model is assumed to proceed without sedimentation removal and results are remarkably insensitive to using a more complicated fall velocity computation method, such as one dependent upon Reynolds number (Pruppacher and Klett 1997). All of our tests are limited to the iteraction of liquid drops.

3. NUMERICAL METHODS

We begin by testing numerical methods used by each model to integrate the stochastic collection equation since errors associated with the numerical method may naturally affect the results of subsequent parameterization tests. We compare two newer methods (Bott 1998; Jacobson et al. 1994) with the classical method derived by Berry and Reinhardt (1978). In subsequent discussion, we refer to these three methods as Bott's, Jacobson's, and Berry's. To compare them most simply, we use the Long (1974) collection kernel, as adjusted by Seifert and Beheng (2001).

The Berry method remains the standard against which other methods can be compared, but is unstable when bin resolution is as coarse as in today's three-dimensional cloud simulations. We find that the Bott method provides an excellent alternative to Berry that is stable at low bin resolution, but predicts some cloud water remaining at the end of the simulation, a feature not produced by the other two methods. We find that the Jacobson method, while also stable, is significantly more diffusive than the other two methods. However, we derive a correction to the Jacobson method that is inspired by Bott's central flux-limiting concept and is equally successful in controlling numerical diffusion. With this correction in place, the Jacobson method provides an accurate and stable alternative to Berry, as well.

4. COLLISION AND COALESCENCE EFFICIENCES

Turning next to the most fundamental parameterization of collision-coalescence, we evaluate the basic gravitational collection kernels. We first compare the Long kernel with that of Hall (1980) and Pinsky et al. (2001) at the 1000 mb level. Whereas the simple analytical Long kernel requires no separate dependence on coalescence efficiencies (or fall velocities), for the latter two we use each model's standard coalescence efficiency parameterization, to which results with most initial size distributions used here are insensitive (future work will further address this matter). Overall, for distributions of drops with mean sizes exceeding ap-

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proximately 8 micrometers, we find results are surprisingly insensitive to differences in the gravitational collection kernel, with differences often on the order of errors associated with Bott's numerical method versus Berry's.

5. BREAKUP

To test the effect of breakup on the equilibrium box size distribution, we use the Low and List method (List et al. 1987). The two models implement this complicated and computationally expensive parameterization differently owing to its most natural integration with either the Berry and Bott numerical methods or the Jacobson numerical method. While rate of rain formation is not affected by inclusion of breakup, the rain in the box now reaches an equilibrium size distribution determined by the coupling of the collision and breakup kernels. We find that the equilibrium time predicted by the two models is negligibly different, but that the equilibrium mean size is different by almost a factor of two.

6. TURBULENCE

The differences between the gravitational collection kernels pale dramatically when the influence of turbulence is included. Here we compare the method of Saffman and Turner (1956) with that of Pinsky and Khain (2002), which we refer hereafter as the Saffman and Pinsky methods. The Pinsky method is currently only applicable for low-level turbulence intensities of order 100-200 $cm^2\ s^{-3}$ typical of early cumulus clouds. The Saffman method scales with turbulence intensity, but is limited to interaction of drops that differ by less than a factor of two in diameter and drops of significantly different size are not considered. Saffman gives a significantly faster rain formation rate, and the two methods appear similar when the Saffman method is limited to collisions of drops that are within about 20% of one another's size. This points the way to a possible scaling of the Saffman method with the better-established Pinsky method. Results produce somewhat different final size distributions and rain formation rates. However, until better data are available, a parameterization for the impact of turbulence that scales with intensity is highly desirable, especially for deep convection, which may reach turbulence intensities that exceed 2000 $cm^2\ s^{-3}$ or more. We also note that the method of Pinsky, wherein the gravitational kernel is multiplied by a factor that varies with the size of the drops, deviates markedly from the Saffman method, wherein the gravitational kernel is changed by a multiplicative factor as well as an additive factor that allows identically-sized droplets to collide. The potential importance of this to initial spectral broadening and rain formation seems evident.

7. SUMMARY AND CONCLUSIONS

We evaluate the most commonly used means of solving the stochastic collection equation in size-resolved cloud models. We find that numerical method is important and derive a correction to the Jacobson method, bringing results in line with the Bott method. While the choice of collection kernel is not as important, turbulence impacts appear profoundly important to the rain formation rate, although existing parameterizations are lacking in range of applicability. We expect much new research to soon be available to improve representation of turbulence effects in such models.

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